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BRIDGE QUALITY APPRAISAL METHODOLOGY: APPLICATION IN THE STRIMONAS BRIDGE. CASE STUDY

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Abstract. In the current utilization of Performance Indicators for bridge Quality Control, there is no correlation between observed and benchmarked Performance Indicator values, and an ambiguity of deliverables due to the diverse nature of Performance Indicators. For the alleviation of those above, this paper presents a methodology that appraises the quality of bridges. This methodology builds on the adaptation of the Sustainable Building Method and its combination with expert input solicitation methods and the research findings of COST Action TU1406. In addition, it features an adaptation of the Analytical Hierarchy Process. The methodology is presented regarding its general procedural steps and calculating requirements, and then it is tailored to the case study of Strimonas Bridge in Greece.

Keywords: analytical hierarchy process, bridges, performance, project management, quality control.

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Introduction

The use of Performance Indicators (*PIs*) for bridge Quality Control (QC) offers the following advantages:

- the to-the-point expression and measurement of crucial bridge quality aspects, such as sustainability (Padgett & Tapia, 2013), serviceability (Liang, Wu, Huston, Liu, Li, Gao, & Ma, 2018), and safety (Zhang & Wang, 2017);
- their measurement diversity, since it is possible to obtain the application data in various ways (e.g., field measurements, laboratory experiments, or expert input) (Ghosn, Dueñas-Osorio, Frangopol, McAllister, Bocchini, Manuel, ... & Akiyama, 2016);
- aiding in decision-making for lifecycle provision, along with the current quality assessment (Frangopol, Dong, & Sabatino, 2017) and
- the existence of lessons-learned from the implementation of *PI*s in project management (Barone & Frangopol, 2014).

Each framework of analysis utilizes distinct procedures to extract and process *PI*s (Frangopol, Strauss, & Kim, 2008). However, in bridge QC, frameworks where measured *PI* values are correlated with their benchmark values of expected and best achievable performance, are so far missing from the current relative implementation. It is possible for such a correlation to allow for a deeper understanding of the nature of the *PIs*, their context within certain quality performance aspects (Key Performance Indicators (*KPIs*), as defined by TU1406), and the way to improve such aspects. In addition, due to the diversity of the *PI*s, the deliverables of existing frameworks are often ambiguous.

In this paper, a general methodology to appraise the quality of bridges is presented, and then it is tailored for the case study of the Strimonas Bridge in Greece. The presented methodology aims to alleviate the drawbacks above in *PI*-oriented bridge QC, by:

- incorporating benchmark *PI* values,
- producing concise quality performance values for the components and the whole bridge, and
- monitoring the intermediate procedural levels through a clear and systematic structure of the methodology.

1. Methodology

Strauss, Ivankovic, Matos, & Casas (2016) have so far identified 55 *PI*s, clustered under the following broader categories:

- general defects,

- material properties,
- the condition of auxiliary and protective equipment,
- structural geometry changes,
- bearing capacity,
- structural integrity and joints defects,
- attributes of the original design and construction sequence,
- dynamic behavior,
- auxiliary characteristics, and
- component cost and importance.

The *PI* values are obtained, depending on the case, during the inspection, monitoring, and maintenance processes, through common ways such as measurements and observations using the particular equipment.

The *PI*s are discretized between the following eleven identified *KPI*s, thus providing the respective quality: availability, costs, durability, environment, health, maintainability, politics, rating/inspection, reliability, safety, and security. It is possible to assign specific *PIs* to multiple *KPIs* (Strauss, Ivankovic, Matos, & Casas, 2016). In addition, depending on the case study, some *PIs* are potentially omitted or restated (Strauss, Ivankovic, Matos, & Casas, 2016). However, all eleven *KPIs* are present in all cases (Strauss, Ivankovic, Matos, & Casas, 2016).

These *PIs* and *KPIs* are presently used as input for the adaptation of the Sustainable Building (SB) Method – a generic framework for building sustainability performance assessment (Mateus & Bragança, 2011) – into a methodological framework for bridge *QC*. Mainly, the SB method initially features the following steps (Mateus & Bragança, 2011):

- identification of the dimensions of the sustainability performance observed in a building;
- discretization of these dimensions into specified subdimensions called Indicator Group Categories (IGCs);
- discretization of IGCs into *PI* notations, namely the various basic elements constituting the IGCs;
- discretization of the *PI* notations into Indicator Parameters (IPA). The IPAs are quantified and benchmarked through:
    - the actual (real practice) values obtained during the inspection, monitoring, and maintenance processes,
    - the conventional (standard practice) values, namely the base thresholds derived from regulatory frameworks and practical experience, and
    - the best practice values, namely the optimal thresholds, derived from regulatory frameworks and state-of-the-art.
- mathematical processing of these value triplets to produce the normalized (in the interval [0,1]) IPA values;

- relative weights assignment for:
  - the IPAs related to the respective *PI* notation,
  - the *PI* notations related to the respective IGC,
  - the IGCs related to the respective sustainability dimension, and
  - the sustainability dimensions related to the overall sustainability performance of the building; this is required, since the importance of the respective elements is potentially unequal to the group in which they belong.
- calculation of the sustainability score of the building, by systematically using weighted sum utility functions: from the IPAs to the *PI* notations, from the *PI* notations to the IGCs, from the IGCs to the sustainability dimensions, and from the latter to the overall building sustainability score. The final score is within the interval [0, 1].

While adapting the SB Method for bridge QC several adjustments utilizing the *PI*s and *KPI*s of TU1406 are made, such as the replacements:

- of the IPAs with the TU1406 *PI*s,
- of the IGCs with the TU1406 *KPI*s,
- of the sustainability dimensions with the bridge components.

The method applied to compute the relative weights of the *PI*s, *KPI*s and bridge components is the same for all three cases, so it is at this moment presented only for the *PIs*. The implemented methodological steps are the following:

1. importance rating of the g *PI*s ($g = \{1, 2, \ldots, l\}$) connected to each of the h *KPI*s ($h = \{1, 2, \ldots, m\}$) using a 5-point Likert scale, ranging from 1 (not important) to 5 (very important); for such rating, the input is solicited from k ($k = \{1, 2, \ldots, n\}$) experts appropriately, such as with a questionnaire survey (Shao, Yuan, & Li, 2017);
2. processing of the input of each of the k experts via the Row Geometric Mean Method (RGMM) variation of the Analytical Hierarchy Process (AHP) (Ishizaka & Labib, 2011), to calculate each of $w_{PI_{gh},k}$, which is the relative weight of the g^{th} *PI* corresponding to the h^{th} *KPI* according to the k^{th} expert;
3. consolidation of all $w_{PI_{gh},k}$ for all n experts to calculate $W_{PI_{gh}}$, namely the relative weight of the g^{th} *PI* corresponding to the h^{th} *KPI* according to all experts, via an AHP results consolidation methodology developed by Goepel (2013) that incorporates the Eigenvector Method (EVM) variation of the AHP (Alonso & Lamata, 2006), and the Weighted Geometric Mean Method (WGMM) (Xu, 2000).

As mentioned above, the same procedure is implemented to calculate $W_{KPI_{hu}}$ (the relative weight of the h^{th} *KPI* connected to the u^{th} bridge component), and W_{comp_u} (the relative weight of the u^{th} component about the bridge as a whole), where $u = \{1, 2, \ldots, v\}$.

After the assignment of all relative weights and following the steps of the SB Method, the values of actual measurement P_{gh}, standard practice P_{gh*}, and best practice P^{*}_{gh} for each of the *PIs* are obtained; finally, the normalized value P^{norm}_{gh} of the g^{th} *PI* affecting the h^{th} *KPI* is computed (Mateus & Bragança, 2011).

Finally, the following boundary conditions are applied to produce P^{norm*}_{gh} the calibrated normalized values and their weighted aggregation into the *KPIs*, and to avoid distortions in the calculation of the P^{norm}_{gh} values:

- if $P^{norm}_{gh} > 1.2$, then $P^{norm*}_{gh} = 1.2$ (International Initiative..., 2009);
- if $P^{norm}_{gh} < -0.2$, then $P^{norm*}_{gh} = -0.2$ (International Initiative..., 2009);
- if $P_{gh} = P_{gh*} = P^{*}_{gh}$, then $P^{norm*}_{gh} = 1$;
- if $P_{gh} \neq P_{gh*} = P^{*}_{gh}$, then $P^{norm*}_{gh} = 0$;
- in any other case $P^{norm*}_{gh} = P^{norm}_{gh}$.

Having all P^{norm*}_{gh} values, the next steps presented in the sequence of implementation are:

- the calculation of the quality performance of the h^{th} *KPI* corresponding to the u^{th} component,
- the computation of the quality performance of the u^{th} component, and
- the calculation of the quality performance of the whole bridge as a system.

Q_{bridge} is the final deliverable of the showcased methodology. It is the qualitative normalized score depicting the quality performance of the bridge, regarding the relative *KPIs* and *PIs*.

2. Application of the methodology in the Strimonas Bridge case study and results

The Strimonas Bridge, which is depicted in Figure 1, is located at coordinates 40°48'4"N, 23°51'20"E. It intersects the Greek part of the Strimonas river, and is part of the 670-km-long Egnatia Motorway (from Igoumenitsa to Kipoi-Evros) that was designed, constructed and is operated by *Egnatia Odos S.A.* (Panetsos, 2017).

The Strimonas Bridge, which was constructed in 1987, is 240 m long, and the width of its pavement (including the sidewalks) is 12 m, providing two traffic lanes. It features eight 30 m long spans, and its deck comprises five precast prestressed concrete T-beams. It is founded on the riverbed of Strimonas with multi-column piers through piles;

Figure 1. The Strimonas Bridge (Panetsos, 2017)

upon the piers, the deck of the bridge is simply supported through NB1 elastomeric bearings. Its expansion joints are elastomeric and of the T50 type. Finally, its identified components are the following: abutments, piers, superstructure, safety railings, sidewalks, pavement, and drainage system (Panetsos, 2017).

For the importance rating of the *KPI*s and components, a questionnaire survey was conducted between the three *Egnatia Odos S.A.* experts directly responsible for the inspection and rating of the Strimonas Bridge. The survey consisted of three sections, with the first one being the identity as shown in Table 1, and the rest featuring:

- seven questions regarding the Likert importance of all *KPI*s for the quality rating of each component, and

Table 1. The identity of the questionnaire survey

Attributes of the respondents			
Researcher	Owner	External partner	
33.3%	33.3%	33.3%	
Expertise of the respondents			
Maintenance	Analytical research	Experimental research	Design
100%	66.7%	33.3%	33.3%
Years of experience*			
[5–10]	[15–20]		
66.7%	33.3%		

Note: *Intervals are determined based on the actual values reported by the respondents in the survey.

- one question regarding the Likert importance of the components for the quality rating of the whole bridge at the system level.

The discretization of the identified *PIs* between the respective *KPIs* and components is shown in Table 2.

Table 2. Identified and discretized Performance Indicators for the Strimonas Bridge

Identified Performance Indicators	Key Performance Indicators											Components						
	A	C	D	E	H	I	M	P	R	S	Se	AB	PI	SU	SR	SI	PA	DS
Approach slab settlement	■	■				■				■	■	■		■	■		■	
Asphalt pavement cracking	■	■				■				■							■	
Asphalt pavement wearing and tearing	■	■				■				■							■	
Asphalt pavement wheel tracking and undulation	■	■				■				■							■	
Bearings deformation	■	■				■			■	■		■	■	■				
Bearings displacement	■	■				■			■	■		■	■	■				
Carbonation depth	■	■	■	■		■						■	■	■		■		
Carrying capacity factor										■		■	■	■				
Chloride content	■	■	■	■		■	■					■	■	■	■	■		
Concrete cover (insufficient)	■	■	■	■		■	■		■	■		■	■	■		■		
Condition rating	■	■				■	■			■		■	■	■	■	■	■	■
Corrosion (overall)	■	■	■		■	■	■		■	■					■	■		■
Corrosion related to prestressing steel	■	■	■		■	■	■		■	■				■				
Corrosion stains related to protective coating	■	■	■			■	■		■	■		■	■	■	■	■		
Corrosion related to reinforcement steel	■	■	■		■	■	■		■	■		■	■	■		■		
Crack length (component-specific causes)	■	■				■	■					■	■	■		■		
Crack orientation (component-specific causes)						■	■					■	■	■		■		

Identified Performance Indicators	Key Performance Indicators											Components						
	A	C	D	E	H	I	M	P	R	S	Se	AB	PI	SU	SR	SI	PA	DS
Crack spacing (component-specific causes)						■			■			■	■	■		■		
Crack width (component-specific causes)	■	■	■			■			■	■		■	■	■		■		
Cracks related to the origin (e.g., due to settlement)						■			■	■		■	■	■		■		
Damping									■	■		■	■	■				
Deterioration of protective coatings						■						■	■	■	■	■		■
Ductility							■		■	■		■	■	■	■			
Frequency									■	■		■	■	■				
Grouting deficiency	■	■	■			■			■	■				■		■		
Inadequate clearance and accessibility							■					■	■	■				■
The insufficient height of the railing (safety barrier)		■				■					■				■		■	
Joint deterioration	■	■				■			■	■		■	■	■				
Loss of section	■	■				■			■	■		■	■	■	■	■		■
Misalignment						■				■	■	■	■	■	■	■		
Pitted corrosion			■			■			■	■		■	■	■	■	■		
Priority repair ranking	■	■					■					■	■	■	■	■	■	■
Probability of failure									■			■	■	■	■	■	■	■
Remaining service life		■	■									■	■	■	■	■	■	■
Sag and deformation and denivelation						■				■	■	■	■	■	■			■
Settlement						■			■	■		■	■	■	■			
Sum of costs for repair of individual damages		■										■	■	■	■	■	■	■
Water penetrability			■			■			■	■		■	■	■				
Waterproofing deterioration and loss	■	■				■						■	■	■				

Note: A = Availability; C = Costs; D = Durability; E = Environment; H = Health; I = Inspection and Rating; M = Maintainability; P = Politics; R = Reliability; S = Safety; Se = Security; AB = Abutments; PI = Piers; SU = Superstructure; SR = Safety Railings; SI = Sidewalks; PA = Pavement; DS = Drainage System

Table 3. All values of the Performance Indicators expressing Key Performance Indicators "Durability" about the superstructure of the Strimonas Bridge

Performance Indicators	Measurement	Unit	P_{gh}	P_{gh*}	P^{*}_{gh}	P^{norm}_{gh}	P^{norm*}_{gh}
Carbonation depth	Carbonation depth	mm	8	10	5	0.40	0.40
Chloride content	Chloride content	%	0.08	0.08	0.04	0	0
Concrete cover (insufficient)	Affected area	%	20	5	0	-3	-0.20
Corrosion (prestressing steel)	Affected area	%	10	1	0	-9	-0.20
Corrosion (reinforcement steel)	Affected area	%	15	1	0	-14	-0.20
Crack width (shrinkage)	Width	mm	0.05	0.20	0	0.75	0.75
Crack width (longitudinal)	Width	mm	0.50	0.20	0	-1.50	-0.20
Grouting deficiency	Strands	%	10	5	0	-1	-0.20
Pitted corrosion	Affected area	%	15	5	0	-2	-0.20
Remaining service life	Number of years	year	15	28	48	-0.65	-0.20
Water penetrability	Affected area	%	100	10	0	-9	-0.20

With all importance ratings obtained as above, the relative weights of all applicable *PI*s, *KPI*s, and components were calculated and then assigned with the process delineated in the Methodology section above.

After the assignment of all relative weights, the three values P_{gh}, P_{gh*}, P^{*}_{gh} of each *PI* were derived from the visual inspection conducted in 2017, catastrophic and non-catastrophic (e.g., magnetic) laboratory tests, and structural health monitoring ambient vibration procedures performed on the bridge (Panetsos, 2017). With all the triplets of the values of the *PI*s obtained, P^{norm*}_{gh} was calculated. As an example, the values for all the *PI*s expressing the *KPI* "Durability" about the superstructure of the bridge are shown in Table 3.

After the calculation of P^{norm*}_{gh}, the quality performance of all *KPI*s corresponding to all components, of all components about the bridge in the system level, and of the whole bridge itself, were respectively computed. The results are summarily shown in Table 4.

For better comprehension of the deliverables of the methodology, Figure 2 is shown. In it, the individual quality scores of the components, their weighted significance, their total scores (namely, the products of the individual quality scores and the weighted significances), and their percentile participation in the quality score of the system level (*Qbridge*), are depicted.

Table 4. Quality performance of the components and system of the Strimonas Bridge

Component	Abutment	Pier	Superstructure	Safety rail	Sidewalk	Pavement	Drainage system
Notation	Q_{abut}	Q_{pier}	Q_{super}	Q_{srail}	Q_{side}	Q_{pave}	Q_{drng}
Q_{compu}	0.112	0.071	0.120	0.650	0.627	0.897	0.189
W_{compu}	0.171	0.218	0.218	0.101	0.087	0.087	0.119
Q_{bridge}	0.281						

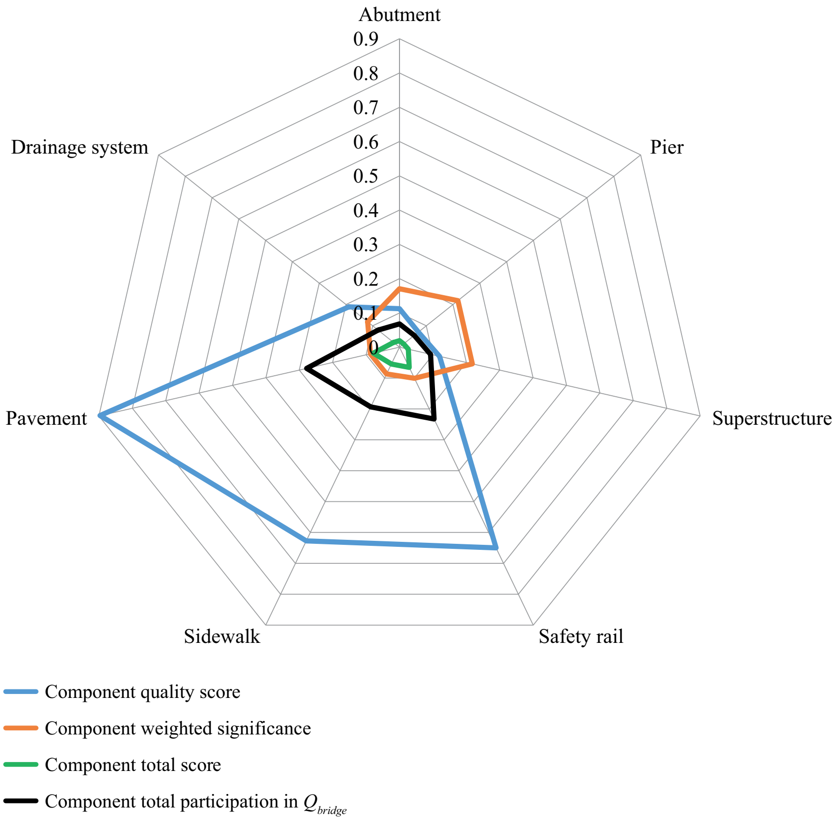

Figure 2. Spider graph depicting the scores, weighted significance, total scores, and total participation of the components in Q_{bridge}

Table 5. Q_{bridge} and proposed quality bridge performance-rating scale

Q_{bridge}	Rating	Characterization	Interval
0.281	A+	Excellent (innovation)	($Q_{bridge} > 1.00$)
	A	Good (best practice)	($0.75 \leq Q_{bridge} \leq 1.00$)
	B	Adequate	($0.50 \leq Q_{bridge} < 0.75$)
	C	Acceptable (common practice)	($0.25 \leq Q_{bridge} < 0.50$)
	D	Poor	($0.00 \leq Q_{bridge} < 0.25$)
	E	Very poor	($Q_{bridge} < 0.00$)

The quality rating scale of the methodology, which is suggested for the interpretation of the final bridge quality score, is an adapted combination of the SB Method quality rating scale (Mateus & Bragança, 2011), and the transposed scale used by Infraestruturas de Portugal for the quality rating and prioritization of existing Portuguese bridges (Amado, 2015). The final quality result is shown, along with the suggested rating scale, in Table 5.

As shown in Table 5, Q_{bridge} = 0.281 translates into a "C" rating and marginally "Acceptable" quality performance. Critical to this generally poor score was, as shown in Table 4, the very low score and very high significance of the piers.

The official Sufficiency Rating (*SR*) of the Strimonas Bridge, as provided by *Egnatia Odos S.A.*, is *SR* = 0.49, with the worst component Condition Rating (*CR*) belonging to the piers (CR_{pier} = 0.333). When qualitatively comparing Q_{bridge} to *SR*, and Q_{pier} = 0.071 with CR_{pier}, it is clear that the presented methodology is much more conservative in its quality appraisal than the one implemented by *Egnatia Odos S.A.* However, it is possible that direct comparison is unsuitable, as the criteria, the scales, and the composition rules of the rating methods are generally dissimilar.

Conclusions

1. The presented methodology, which appraises the quality of a bridge, offers a clear and systematic computational framework, having as deliverables the final bridge quality score at the system level, as well as the intermediate Performance Indicators, Key Performance Indicators, and component quality scores. Thus, the monitoring of the whole process is allowed.
2. It is highly customizable, allowing for the specific weight assignment and Performance Indicators identification and discretization.

3. It is, thus far, the only methodology appraising the quality of bridges, in which the measured values of the Performance Indicators are correlated with their benchmark values of expected and best achievable performance.
4. Its solicited subjective expert input is limited to the initial weighting procedures of the methodology and is only needed once per case study (except special or severe cases).
5. In the present case study of the Strimonas Bridge, the final bridge quality score of the methodology indicates a marginally acceptable, almost poor bridge condition. This indication is in accordance to the official Sufficiency Rating provided by *Egnatia Odos S.A.*, which also indicates a marginally deficient bridge (0.49 < 0.50). Nonetheless, the score of the present methodology is more conservative than Sufficiency Rating, and even the structural condition rating applied by *Egnatia Odos S.A.* that is equal to the worst component Condition Rating (Condition Rating of the pier in the present case).
6. It is advised that more case studies, even featuring radically different bridge typologies, are carried out, for the further calibration of the presented methodology.

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